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REVIEW OF MICROWAVE INSTRUMENTATION AND MEASUREMENTS

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The techniques of making power measurements at microwave frequencies are reviewed. Common types of instruments used for such measurements are evaluated. The supporting concepts of mode structures and Q-factors are discussed, and the methods of determining these properties are examined. Finally, the various techniques for measuring the dielectric properties of materials at microwave frequencies are reviewed.

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To Dr. D. Mills
Director of Research

1.0 INTRODUCTION

This report provides background into some of the techniques and instrumentation required for working with microwaves. The focus is on areas of interest to the Ontario Hydro Electroheat Laboratory. It is not intended to provide a comprehensive overview of the entire field. Several excellent sources are available for that purpose and these are noted in the references. This review will concentrate on four areas, namely, power measurements, modes structures, Q-factors, and finally, the measurement of dielectric properties.

However, before getting to these specifics, it is important to mention one of the most basic points to have in mind when working with microwave circuits. That is, at microwave frequencies the electrical wavelength is smaller than the physical dimensions of the circuit. At 2.5 GHz, which is the usual working frequency in the Electroheat Laboratory, the wavelength is about 10 cm. This is very different from usual power-line or radio frequencies where wavelengths are tens of metres up to many kilometres. The short wavelengths in microwave circuits mean that, resistances, capacitances, and inductances become more distributed throughout the system, and the usual lumped circuit-element analysis is not very useful. In general, a more holistic approach to the circuit must be taken. Taking good measurements, and making sense of the numbers obtained requires an appreciation of the complete circuit. This is why factors like impedance matching and mode structures become very important.

2.0 MEASUREMENTS OF POWER

There are basically four different ways of sensing microwave power:

Radiation Pressure,
Plasma Luminescence,
Thermal Conversion,
Non-Linear Elements.

The first two of these are not very important, and so will only be discussed briefly. Radiation pressure measurements are very delicate and difficult to make, but may be calibrated in terms of fundamental units and so are usually to be found only in standards laboratories. Plasma luminescence, such as in neon glow tubes, is difficult to calibrate and usually found in applications like on/off indicators.

2.1 Thermal Conversion

Thermal conversion sensing is a more common technique with accuracies of one or two percent easily available. Basically it involves converting microwaves into heat and using thermometric techniques to sense the power. This is generally done using either calorimeters, thermistors, bolometers or thermocouples. Calorimeters involve heating a known volume of a well characterized material through a temperature change. They tend to be slow and bulky, and not very useful at low signal levels. They can however provide high accuracy at higher power levels. Thermistors and bolometers are smaller devices whose electrical resistance changes with the temperature. Response times are about one second for thermistors and of the order of milliseconds for bolometers. Instruments with these elements usually require some form of temperature compensation for drifts in ambient temperatures in order to attain high accuracy. A third thermal conversion technique of coupling the microwave power directly to thermocouple sensors is sometimes used however there are problems with matching power sensitive elements. There has been progress in this area using thin film circuits on semiconductor elements.

2.2 Non-linear Elements

The sensing method most commonly employed at Ontario Hydro involves using non-linear elements such as rectifiers or frequency mixing diodes. With these devices the microwave frequencies are either converted to dc signals or mixed down to lower frequencies where conventional electronic techniques may be applied to the measurement. The measurement may be as simple as measuring the dc voltage developed across the terminals of a crystal diode, or as complex as mixing the microwave signal with a swept reference frequency and displaying the result in a network analyzer.

The diodes used for this are relatively cheap and dependable. They can have excellent sensitivities even at low power levels. However, they generally suffer from having uncertain response laws. As a first approximation they are square law detectors, that is, the current across their terminals will vary with the square of the impressed microwave voltage. But even for currents as low as one microamp, response will deviate from the square law to a more linear response. The sensitivity of these detectors is also dependent upon temperature, as well as the polarization of the incident radiation. Failure to allow for these additional sensitivities can easily result in systematic errors of tens of percent.

These problems are best dealt with by carefully calibrating the detector for each specific coupling to the microwave circuit. Unfortunately this is not always practical since the diode may have to be moved. In this case it is important to insert the sensing element into the microwave circuit so that the coupling is changed in a known way or, most preferably, not changed at all. This can be done by mounting the diode in a keyed socket, on a rigid carriage, or on something similar. The situation is very different from a conventional electric voltage probe which may be inserted anywhere into a circuit. When working with a microwave probe, a calibration is usually specified for a given position and orientation of the sensing element, and this should be changed as little as possible.

2.3 Coupling

The foregoing covers the basic methods used for sensing microwaves (see also the appended summary table); however, for making complete power measurements it is appropriate to consider the topic of coupling. As an example of this, consider the common problem of measuring high powers with sensitive diode detectors. The difficulty here is to select out a small representative sample from the main power flow and remove it for measurement. For this purpose T-junctions are frequently used. T-junctions are good for power division ratios of up to 10:1 and are easy to calibrate, but are not appropriate for higher powers and are sensitive to impedance mismatches. Another device is the directional coupler which can offer higher division ratios as well as the ability to sample the power flow in a selected direction (see Fig.1). Directional couplers are also easy to calibrate and very stable, they are available in a wide variety of division ratios.

Coupling is also important to consider when interpreting the numbers obtained in a power measurement. For example, it makes no sense to measure the power flowing forward through a transmission line and claim that it is the power produced by the generator, or the power delivered to the load. If the line is poorly coupled at its ends, the generator may not be able to deliver its full output into the line, and the load may in turn be incapable of admitting the delivered power. As a general rule, in a microwave system, the impedance matching of the elements must be considered before power measurements can be meaningfully interpreted. These ambiguities may be reduced by properly coupling circuit elements as a standard laboratory practice. This can be done using isolators, attenuators and circulators. Any remaining mismatches may be dealt with by measuring reflection coefficients and phase shifts and incorporating these into the power 'measurement'.

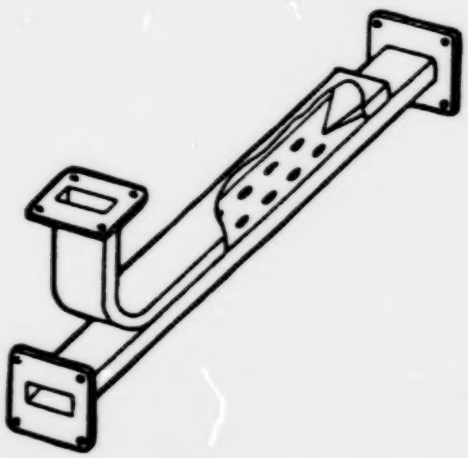

Fig. 1 Example of a typical directional coupler. A fixed fraction of the forward energy flow through the straight section is directed to the third port.

3.0 MODE STRUCTURES

When microwave radiation is confined inside waveguides and applicators, it will be constrained by these boundaries to oscillate only in certain patterns. These patterns directly affect the distribution of energy throughout the volume of the system. They are usually called modes of oscillation, or just modes.

A familiarity with common mode patterns is important for two situations encountered in the Electroheat Laboratory. First, when energy flows are being measured, it is important to understand how the energy in waveguides is distributed so that it can be sampled properly. And second, an understanding of applicator mode structures is important for

uniform product heating. This section will discuss the common mode patterns found in waveguides and applicators used in the Industrial Electroheat Laboratory.

3.1 Propagation Modes in Waveguides

High power microwave radiation is usually directed from place to place in waveguides with a rectangular cross section. In the Electroheat Laboratory, the long edge of the rectangle is either 7.21, or 8.64 cm long, and the short edge is half that length. Although there are many modes in which the microwaves may travel down such a tube, only one mode is important in common practice. This is the TE_{10} mode. It is distinguished from the other modes by its simplicity and its low frequency. The mode is composed of a complex pattern of electric and magnetic fields; however, since virtually all of the effects of interest are related to the electric field, only this part of the pattern is of practical importance.

The electric field of the TE_{10} mode is indicated in Fig.2. It goes straight up and down between the long sides of the rectangle. It is weakest alongside the short edges, and strongest near the center. Accordingly, if a power measuring probe is inserted along the short side, it will measure only a small fraction of the average field. As it moves closer to the center, a more intense field will be encountered. Also note that the field is linearly polarized. Therefore, if the voltage probe is sensitive only along a particular axis, that axis has to be aligned with the field axis in order to sense the entire field strength at that point.

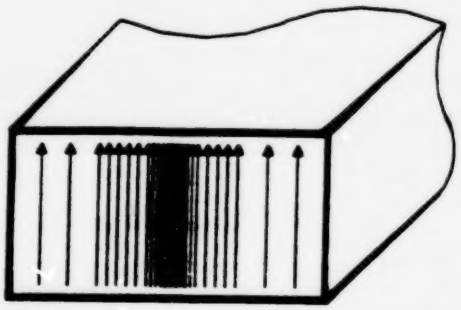

Fig. 2 Electric field vectors in a waveguide operating in the TE_{10} mode.

3.2 Standing Waves

The foregoing describes the transverse structure of the waveguide field for almost all working conditions. Unfortunately, it is not so simple to sum up the longitudinal pattern. This is because the variation along the length of the waveguide depends critically upon the way the waveguide is matched to the generator and the load. Whenever there is an impedance mismatch at the ends of a waveguide, some fraction of the power will be reflected back along the line. This reflected wave will combine with the forward wave to form a stationary interference pattern known as a standing wave. The energy density along the length of the waveguide will be modulated by this standing wave.

The standing wave is usually described with a single number, the voltage standing wave ratio, or VSWR. This is just the ratio between the peak voltage and the minimum voltage along the waveguide. When there is no standing wave, the time averaged field strength is constant along the length of the line, so there are no peaks or minima, and the VSWR is equal to one. When reflections are present, a standing wave mode is established, and the VSWR becomes greater than one.

If power measurements are being made in a waveguide, and a standing wave is present, then the position of the probe along the length of the guide will be important. Usually, the best way to establish whether or not this the case, is to slide the probe along the

waveguide and look for variations in the voltage. This has to be done without changing the part of the cross section which is being sampled because of the transverse variations discussed earlier.

Another situation where standing wave modes are important is with slotted guide applicators, or serpentine applicators (see Fig.3). In this case the heating power will vary along the length of the applicator because of the standing wave. In many cases, the shape of the standing wave can actually be seen on the product as the effect of uneven treatment. These problems can be dealt with by changing the termination of the waveguide to minimize reflection and reduce the VSWR.

3.3 Multimode Applicators

Consider now the mode patterns in microwave oven applicators. In an oven cavity, there are usually multiple reflections off of the walls and the sample itself. These many waves will bounce around and add up with each other to form a wide variety of energy distribution patterns. In the worst case, this can mean a complicated pattern of undesirable hot spots. However, since each mode usually has its peak energy density in a different position, it is possible to get fairly uniform heating by operating as many modes as possible. In a typical oven, fifty or sixty different modes are oscillating.

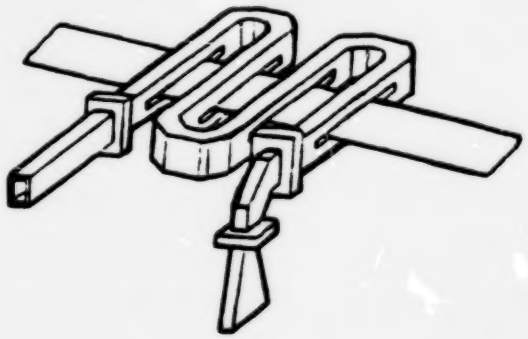

Fig. 3 Example of a serpentine applicator. The product web passes through multiple slots in the waveguide.

It is not practical to consider each mode individually since its position and energy content will strongly depend on the shape, position and composition of the sample to be heated. However, one way of dealing with this is to try to spread the energy into as many modes as possible by using mode stirrers, or multiple feed-ins. Another common approach is to move the sample in the cavity during treatment. This has the effect of changing the mode pattern, and more importantly, it exposes different parts of the sample to any persistent hot spots to obtain more uniform average heating.

4.0 MEASUREMENTS OF Q-FACTORS

In broad terms, Q-factors are used to describe how intensely a system will resonate. For microwave systems, one is usually concerned with resonances within a cavity. In this case the word resonance refers to the preferentially enhanced storage of energy in the cavity. This storage can occur as the microwaves oscillate back and forth in some vibratory mode of the system. Of course, the amount of storage will depend on how much energy gets into and out of the cavity. These flows are determined by the coupling impedances between the cavity, the generator, and what ever losses are present. The coupling impedances are frequency dependent. Since the various impedances do not all have the same frequency dependence, there is usually some particular frequency for which the gains and losses will add up to give more storage than for other frequencies. Operating at this frequency gives preferentially enhanced energy storage, or resonance. Q-factors describe the sharpness of this resonance peak.

Q-factors are of interest in electroheating because resonant cavities are frequently used as applicators. A high Q cavity will develop very intense electric and magnetic fields as the microwave energy builds up to resonance. Since the heating power transferred to a product varies with the square of the electric field strength, a high Q-factor can mean high power heating capacity. An example of this is the use of high-Q cavities with ceramic products. At room temperatures, these materials may be impossible to process with available powers unless that energy is applied under resonant conditions, a high-Q applicator may therefore be required. However, a high-Q factor is not always desirable. For example, an improperly loaded, high-Q cavity can produce dangerous arcing as the electric field strength builds up beyond the breakdown voltage of air.

To make things more specific, the Q-factor can be simply defined as,

$$Q = 2\pi \times \frac{\text{Energy Stored in the Cavity}}{\text{Energy Dissipated per Cycle}}$$

although numerous other equivalent definitions are possible. From this definition, it is apparent the Q will strongly depend on how the cavity is loaded since this affects both load losses and other coupling factors. These considerations of coupling and dissipation are usually brought together in what is known as the coupling constant,

$$\beta = \frac{\text{Externally Dissipated Power}}{\text{Internally Dissipated Power}}$$

The cavity is called overcoupled if β is greater than one, undercoupled if β is less than one, and critically coupled when equal to one. Knowledge of the coupling constant is usually required when analyzing Q-factor measurements. If it is not known ahead of time, it is usually determined in the measurement procedure.

4.1 Measurement Techniques

Roughly speaking, there are three ways of determining Q-factors:

Measuring transmitted power.
Measuring cavity impedance.
Dynamic methods.

The first two techniques are essentially bandpass measurements involving observations of the circuit response to continuous wave signals in the neighborhood of the resonant frequency. They are usually used for low or intermediate Q's. For higher values, the last method using swept or pulsed signals is preferred.

Measuring transmitted power is one of the most straightforward ways of determining Q. With this method, the frequency is varied near resonance, and the power transmitted through the cavity to a detector is recorded. The transmitted power will dip to a minimum as the frequency passes through resonance because at resonance, the cavity will be storing more power. If ν is the resonant frequency then

$$Q = \alpha\nu/\Delta$$

where Δ is the bandwidth between points where transmitted power is a fraction Φ of the observed change. The factor α is given by $\alpha^2 = (1-\Phi)/\Phi$. The numbers are particularly simple if the bandwidth is measured at the half power (or -3 dB) points. In that case, Q is just the ratio of the bandwidth to the resonant frequency.

Measurements based on impedance observations are very similar to the power measurements. They are used when there is no second port to the cavity to use for power transmission. In this case the VSWR, reflection coefficients and/or the phase shifts in the supply line are measured as a function of the frequency. These quantities will change in one of several specific patterns depending on whether the coupling coefficient, β, is greater or lesser than one. The patterns may then be analyzed to obtain Q according to standard procedures and formulae. See Ref.1 for worked-out examples of these calculations.

The third class of dynamic measurements are based on observing the response of the cavity to signals which are swept or pulsed. For example, a network analyzer may quickly sweep through a range of frequencies and determine the Q by continuously monitoring the transmitted power. Another example is the decrement method where the decay time of a short burst of input energy is monitored to determine Q. Specialized instruments are available for making these dynamic measurements, and the details of the experimental procedure vary with the instrument.

4.2 Systematic Errors

Aside from the particulars of any particular method of measuring Q, there are some general points to be made. Measurements of the properties of resonant circuits are particularly sensitive to fluctuations in frequency and changes of impedance. To obtain good data it is necessary to ensure that the microwave system has had adequate time to warm up to stable operating conditions. For the generator to operate stably, it should be well matched to the load. Attenuators and circulators are usually better for this than tuners because their bandwidth is wider. It is also important to minimize adverse vibration and hum from blowers and cooling water since this can modulate the operating frequency.

As an example of the importance of these points, consider trying to measure the properties of a cavity with a fairly small Q of just one hundred. At the standard operating frequency of 2.5 GHz, the half power bandwidth will be 25 MHz. If we want to measure this to within five percent, a stability of about one MHz is required. That means frequency stability of five parts in ten thousand is required. Clearly some careful attention to obtaining stable operating conditions are necessary, even for such a relatively low Q-value.

5.0 MEASUREMENTS OF DIELECTRIC PROPERTIES

The electromagnetic properties of uniform dielectrics may be characterized by one complex number known as the complex dielectric constant, ϵ^*. There are various conventions for proceeding from this point, but a common development is to set $\epsilon^* = \epsilon_o(\epsilon'-j\epsilon'')$ where ϵ_o is the permittivity of free space. Here ϵ' is associated with the ability of the dielectric material to store electric energy and ϵ'' is associated with the dielectric losses which occur in the material, ϵ'' is sometimes called the loss factor. Another commonly used parameter is the loss tangent, $\tan\delta = \epsilon''/\epsilon'$ which is proportional to the

power lost over the energy stored per cycle. This quantity is directly proportional to the heating produced by the electromagnetic field in the dielectric sample. Unfortunately none of these quantities are really constant. They may vary with frequency, temperature and humidity, and these factors should be controlled in any measurement.

The methods for measuring these dielectric parameters are very numerous, but most will fall roughly into the following categories.

Methods using transmission in a waveguide
Methods using transmission in free space
Methods depending on reflection
Short-circuited line method
Resonant cavity methods

The choice of method is usually dependent upon sample characteristics like size, lossiness, homogeneity, sensitivity to temperature and humidity, whether it is a solid or fluid, etc. Many methods are specialized for a particular type of sample. However, this discussion will focus on just the last two methods.

5.1 Short-Circuited Line Method

The short-circuited line method was developed by von Hippel in his extensive work in this area, and is still probably the most widely used and versatile technique. It is distinguished from other methods by its low sensitivity to errors and non-approximate solutions. It does not require specialized waveguide terminations, and the sample size may be optimized for accuracy rather than being restricted to any particular length. The systematic errors associated with the method are well understood, and few in number. It is useful for most ranges of ϵ^*, especially medium ϵ' and $\tan\delta$.

The technique requires only a slotted line, and a short circuit. The position of a voltage minimum is measured both before and after a known length of sample is inserted in front of the short circuit. Then a transcendental equation of the form $\tan\chi/\chi$ equal to a known constant must be solved. This may be done using either tabulated solutions, graphical means, or with a specialized computing routine. The possibility of multiple solutions exists and, if the dielectric properties are not already approximately known, then this may be dealt with by making two measurements with samples of different length. As the details of this procedure can become quite involved, the reader is further referred to the good discussion in Ref.1 which gives worked-out examples of the calculations. Systematic errors may arise from air gaps around the sample, losses in waveguide walls, or drifts in generator frequency. These are extensively dealt with in Ref.2, Section 10.18.

5.2 Resonant Cavity Methods

Consider now the resonant cavity methods of measuring dielectric properties. These techniques are notable primarily because of the very high sensitivity they can offer. The method is not easy to use, specialized cavities and sample preparations are usually required. In addition, the necessary calculations can be very demanding if standard sample geometries cannot be used. Nonetheless, this method is relevant because of the high level of interest the Electroheat Laboratory is presently taking in applications of microwaves in ceramic processes. Both conventional and advanced ceramics frequently

exhibit low dielectric constants and loss factors. Consequently, a very sensitive technique is required to characterize them.

The basic idea behind the method is to compare the Q-factor and resonant frequency of a cavity with, and without, a sample of the dielectric material inside the cavity. The Q-factor is a measure of the energy stored in the cavity compared to the energy lost per cycle, therefore changes in the Q-factor will reflect the amount of energy lost or stored in the dielectric sample. The method offers great sensitivity because cavities may be constructed to have sharp resonances. This produces very high electric and magnetic field strengths inside the cavity. Under such intense conditions, even relatively small losses have a large enough effect to be accurately measured. The sample may fill the cavity and this is frequently done with fluid samples. However, if the sample does not completely fill the cavity then the required calculations are almost intractable for all but a few cases. For solid ceramic samples, it would probably be best to use perturbation methods. This means adding just a very small amount of dielectric material so that the Q-factors and resonant frequencies change by only a small amount. In this case the necessary mathematics can be greatly simplified, but remain dependent on the particular cavity and sample shapes used. Many specific examples for various configurations are available in the references. The choice from amongst these will strongly depend on the samples, for example whether or not they are produced in standard shapes like spheres or rods, or if they are machinable. One possibility is that if samples are molded into a constant but irregular shape, then it may be possible to mold a material of known dielectric properties into the same shape. In this way it is possible to calibrate the entire cavity/sample configuration without doing extensive calculations.

5.3 Systematic Errors

Finally, it is appropriate to make some general comments concerning sample preparation for dielectric property measurements. Improper sample preparation can produce large measurement errors and this is true of all measurement methods. The most common problem concerns the boundaries of the sample which should be as smooth as possible. Also, if the sample is to be fitted into a waveguide, it must be as close fitting as possible, preferably a forced fit. If it is impossible to eliminate air gaps, it is preferable that they be along the short dimension of the waveguide since the electric field is minimal in this region. It is important to remember that exposure to the microwaves will frequently heat the sample, and that this may cause shrinkage or other distortion as well as actually changing the dielectric properties. A last point is that if the sample is fibrous, layered, or in some other way anisotropic, then it should be oriented in the waveguide with the planes or axes of symmetry orthogonal to the walls.

6.0 SUMMARY

Power measurements are usually made with diodes or calorimeters. Diodes are very sensitive to temperature, position, and polarization, so careful attention to operating under calibrated conditions is necessary to obtain meaningful results. T-junctions or directional couplers are frequently used for sampling power from large energy flows.

When measuring power, any mode structures present in the system should be considered. For most situations using rectangular waveguides, the energy density is highest in the center of the guide and approaches zero alongside the short wall. Standing waves are

usually present in systems with imperfectly matched terminations. They will modulate the energy density along the waveguide, and will cause uneven heating in slotted or serpentine applicators.

Sometimes a system will oscillate in a resonant mode, and this feature is used in several types of applicators. Q-factors are used to describe the sharpness of the resonance. Q-factors may be measured by analyzing the system impedance at different steady frequencies, or by using swept or pulsed signals.

Finally, the interaction of microwave power and a given sample is characterized by the dielectric properties of the sample. For most samples, these can be best measured by the short-circuited line method. However, for low-loss ceramic samples, more complex resonant cavity methods may be necessary.

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SUMMARY OF POWER MEASURING DEVICES

Method	Comments
Radiation Pressure	delicate and difficult to use good for standards labs
Plasma Luminescence	difficult to calibrate
Thermal Conversion	
calorimeters	slow and bulky not good for low powers high accuracy at high powers
thermistors	one second response times cheap and easy to use sensitive to temperature
bolometers	millisecond response times cheap and easy to use sensitive to temperature
thermocouples	problems with coupling to microwaves
Non-linear Elements	
rectifiers and frequency-mixing diodes	cheap and easy to use dependable sensitive at low powers uncertain response laws sensitive to temperature sensitive to polarization

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